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RESPONSE AND DAMAGE EVALUATION OF REINFORCED CONCRETE FRAMES SUBJECTED TO BLAST LOADING

Ruwan Jayasooriya, Queensland University of Technology, Australia
David Thambiratnam, Queensland University of Technology, Australia
Nimal Perera, Robert Bird Group and Queensland University of Technology, Australia
Vladis Kosse, Queensland University of Technology, Australia

Abstract

Bomb attacks carried out by terrorists, targeting high occupancy buildings, have become increasingly common in recent times. Large numbers of casualties and property damage result from overpressure of the blast followed by failing of structural elements. Understanding the blast response of multi-storey buildings and evaluating their remaining life have therefore become important.
Response and damage analysis of single structural components, such as columns or slabs, to explosive loads have been examined in the literature, but the studies on blast response and damage analysis of structural frames in multi-storey buildings is limited and this is necessary for assessing the vulnerability of them. This paper investigates the blast response and damage evaluation of reinforced concrete (RC) frames, designed for normal gravity loads, in order to evaluate their remaining life.
Numerical modelling and analysis were carried out using the explicit finite element software, LS DYNA. The modelling and analysis takes into consideration reinforcement details together and material performance under higher strain rates. Damage indices for columns are calculated based on their residual and original capacities. Numerical results generated in the can be used to identify relationships between the blast load parameters and the column damage. Damage index curve will provide a simple means for assessing the damage to a typical multi-storey building RC frame under an external bomb circumstance.

Keywords: Blast analysis, Reinforced concrete frames, Finite element analysis, LS DYNA Modelling, Damage evolution, Residual capacity, Damage indices.

1. Introduction.

The world has experienced increasing numbers of bomb explosions carried out by terrorists on high occupancy multi-storey constructions in various parts of the world [4, 10]. Figure 1(a) and Figure 1(b) show damage to the Alfred P. Murrah Federal Building in Oklahoma city after the bomb attack in 1995 and damage to the Central Bank of Sri Lanka in 1996, respectively [4, 9]. These incidents demonstrate that the world is under threat of terrorists and understanding the response and vulnerability of multi-storey building to blast loads is impotent to minimize the adverse consequences associated with bomb explosions.

Bomb explosions close to a building may cause casualties from direct overpressure of the blast, followed by falling of failed structural elements such as beams, column or slab. These explosions can also cause millions of dollars of property damage [8].

(a) (b)

Figure 1: Following the bomb attack at (a) Alfred P. Murrah Federal Building Oklahoma City, 1995 (b) Central Bank, Sri Lanka, 1996

Blast assessment of structures is complex because it involves a large number of parameters. These parameters are related to the blast loading and material behaviour under rapid strain rate [8]. Special attention has to be paid to those parameters in evaluating blast response of building structures. Even-though numerous studies have been conducted in the area of blast analysis of multi-storey buildings, the majority have only addressed explosion resisting designs followed by mitigation techniques to offer safety measures at the design stage or later by retrofitting techniques [2, 4, 8, and 16]. Unfortunately, existing buildings, not designed to resist such abnormal blast loads, are also vulnerable to damage under blast loads and the number of such existing vulnerable buildings can be relatively very higher.

As terrorists usually target high occupancy constructions, it is necessary to evaluate the response and damage of multi-storey buildings to explosion load to avoid hazards accompanying bomb attacks. However, few researchers have evaluated the damage and residual capacities especially by studying single structural components such as column, beam or slab, individually [12, 14]. An analysis for reinforced concrete frames under blast loads is vital to assess the vulnerability of multi-storey buildings for both vertical and lateral stabilities. Therefore, this paper discusses the damage analysis of reinforced concrete frames designed for normal gravity loads in order to identify the risk associated with typical bombing incidents. Two principle stages in the damage evaluation process under explosion loads are included here. Firstly, the structural response under typical external blast loads is investigated and secondly, residual capacities of the remaining structure are measured to obtain the state of damage. Numerical analysis has been carried out successfully using explicit LS DYNA program as it is well suited to analysis structures under rapidly varying random loads such as blasts. This software provides the capacity to examine material behaviour under rapid strain rate [6, 11]. Results will be used to calculate damage indices which depend on the residual and original capacities of a structural member. In this paper such damage indices are presented for the front face columns under a given blast loading.

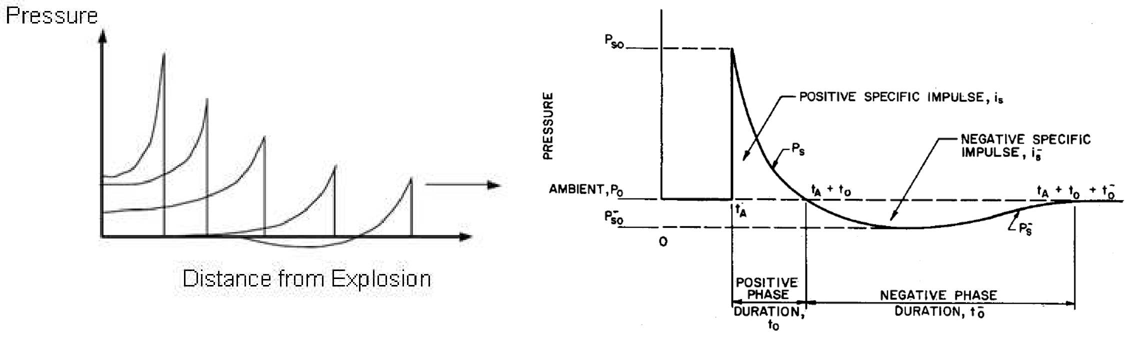
2. Blast Phenomenon and Characteristics.

An explosion can be indentified as a release of energy by chemical reactions on a large-scale in a short period of time. This sudden release of energy changes the surrounding air to a high temperature and very high pressure [3, 13]. Shock waves are then created by propagating high-pressure gas which travels at a very high velocity to areas far from the origin of the incident [13].

Different kinds of explosive materials are used in explosions. Therefore, a datum is necessary to assess the detonation characteristics of each type of explosive material. TNT (Trinitrotoluene) is therefore used as the standard. The effects of various explosive materials are then expressed in terms of standard TNT equivalent mass for of blast prediction and design [16]. The distance available between the source of the blast and the target is called stand-off distance. As all blast parameters depend on the quantity of energy released by the explosion (or charge weight) and distance available to a particular target from the origin of the explosion, a special “scaled distance Z” in evaluates of explosion effects [13,16]. This is illustrated in cube root scaling;

$$Z = \frac{R}{W^{1/3}}$$

Where Z is the scaled distance in m/kg $^{-1/3}$, R is the range from the centre of the charge (Stand-off distance), W is the mass of the spherical TNT charge equivalent. The shock wave generated by the explosion consists of a sudden increase in pressure at the front of the wave which then gradually decreases in pressure behind it. The blast wave variation over distance is illustrated in Figure 3 (a) [13].



(a) (b)

Figure 3: (a) Propagation of overpressure with distance (b) Overpressure - time profile [13]

Pressure variation at a particular point after the explosion with time is described in the overpressure-time profile as shown in Figure 3 (b). It consists of a positive phase followed by a negative phase with different time durations [13]. The area under the cure represents the related impulse caused.
The blast overpressure-time profile is mathematically represented by the Friedlander equation preserving its positive phase only [10],

$$p(t) = p_{so}\left(1 - \frac{t}{t_o}\right)\exp\left(-\frac{bt}{t_o}\right) \qquad ,$$

Where p_{so} is the peak side-on overpressure, t_o is the duration of the positive phase of the blast, b is the waveform parameter t is the time measured from the instant that the blast wave arrives (at time = t_a), $p(t)$ is the pressure at time t.
A simplification of the blast wave profile is made and preserved the positive phase linear variation as shown in Figure 4. The relationship then becomes [16];

$$p(t) = p_o + p_s\left(1 - \frac{t}{t_d}\right).$$

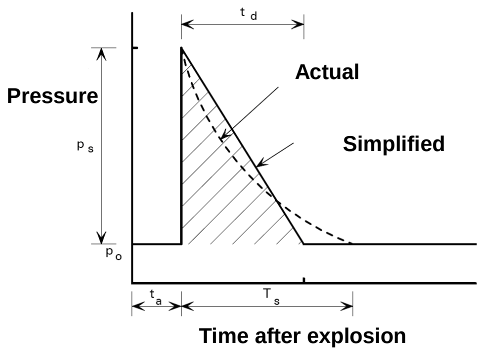


Figure 4: Simplified blast wave overpressure profile [16]

This simplified formula is sufficient to predict blast pressure for conventional analysis, as the positive phase is significant in determining structural response [1, 4, and 16]. Numerical values for these parameters can be obtained from various sources with respect to required scaled distance, z. Technical Manual 5-1300, (1990), is one of a widely accepted key resource to obtain required blast related information [13]. Baker et al. (1983) can also be referenced to find these parameters [1]. In addition, the empirical equations developed by Kingery and Bulmash, 1984 are widely accepted and used to determine explosion related facts [5]. These published sources are usually employed in blast load evaluation phase in structural analysis in most conventional engineering practices [4, 7, and 10]. Present study considered pressure and related parameters for typical loading scenarios created by a car bomb located 10m from the target. Different pressure circumstances were obtained by changing the charge weight used to create the explosion.

3. Blast Response and Damage Evaluation.

3.1 Importance of Damage Analysis.

Damage analysis is important in the decision-making process not only in post blast rehabilitations but also immediately after the blast. Damaged buildings may undergo further collapse due to the lack of strength of lower level elements, some times after the incident. Therefore, rescue workers have to serve with extensive risk. Additionally, assembling the building occupants at a single location may exceed the residual live load capacity and could lead to further collapse of the building. These significant facts simply imply that the demand for a safety evacuation and disaster plan based on damage and collapse consequences of an entire building are paramount.

Level of damage occurred by the explosion is one of significant factors to be considered in post blast evaluation and rehabilitations. Therefore, damage analysis assists engineering decision to completely demolish, partially demolished or repairs of a structure. Level of damage and locations should be determined. Damage evaluation may also support design to resist blast and retrofitting measures as well. Therefore, damage must be measurable and predictable. Therefore, damage indices have to be defined to quantify the damage. It relates to the costs of rehabilitation as well. Current knowledge on quantifying explosion damage is incomplete although necessary and highlights the need for more comprehensive method to describe damage analysis [14].

3.2 Methodology and Computer Simulation.

Computer simulation has become an efficient tool in the analysis of structures especially under random loads. Dynamic analysis of structures by computer modelling enables a more realistic assessment of the performance of structures under time varying loads such as blast loads because it is difficult to carry out experimental studies due to safety issues with explosions [8]. A case study has been conducted here to illustrate the analytical process to assess the damage consequence for a two-storey RC portal frame under explosion loading.

3.2.1 Description of the Case Study.

A two-storey reinforced concrete portal frame is selected to demonstrate the blast and damage analysis procedure. This consists of columns and beams designed for normal gravity loads. Material properties are 40Mpa for the concrete compressive strength, 500 MPa and 300MPa for the yield strength of longitudinal and traverse reinforcements respectively. Transverse reinforcement spacings are as 125 mm beams and 150 mm for columns representing the typical construction specifications. Frame dimensions are lengths 5000 mm centre to centre of the column and 4200 mm height. The column and beam dimension selected for this case study are typical frame element proportions in existing buildings designed for normal gravity loads. Column dimension and arrangement of longitudinal reinforcement of 1% of cross section are provided and illustrated in Figure 5 (a). The beam is 300 mm x 450 mm and the amount of top and bottom reinforcement is 9.2 cm^2 as shown in Figure 5(b). Base columns are assumed to be fixed to the foundation. The bond strength between concrete and steel bar is taken as 20 MPa [12].

3.2.2 Model Development.

Structural analysis has been conducted using LS-DYNA, developed specially for this kind of dynamic analysis of structures [6]. A two storey two-dimensional model is developed in LS DYNA with all longitudinal and transverse reinforced details as shown in Figure 5 (c). Reinforcement is modelled, as line elements while concrete are three-dimensional solid elements. A material model is very important in numerical simulations as the overall results of the analysis are sensitive to material properties utilized and therefore, significant attention had to be paid in selecting the suitable one [11,12].

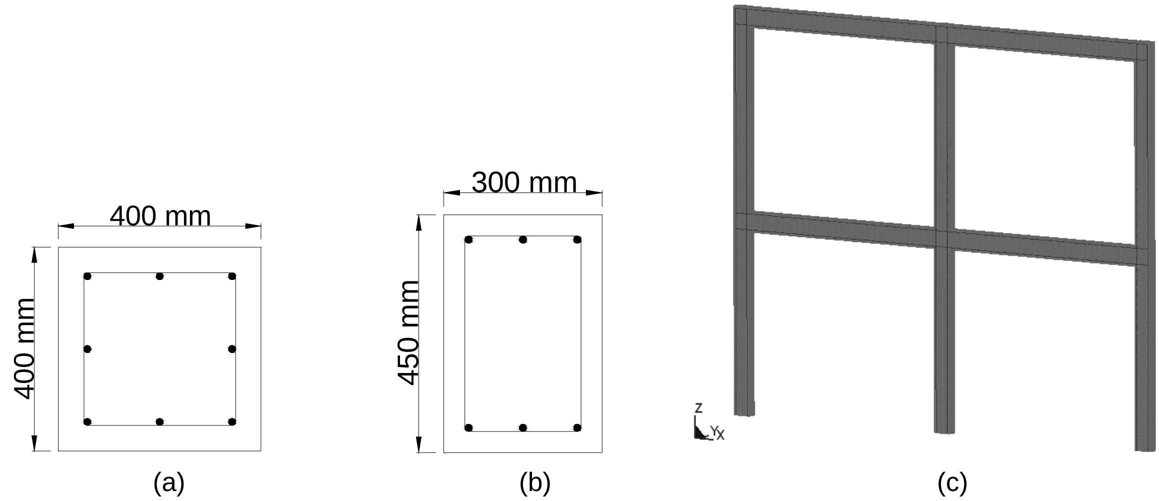


Figure 5: (a) Column dimensions (b) Beam dimensions (c) LS DYNA Model of RC frame

Large numbers of material models are available in LS DYNA to represent concrete. According to literature [11, 12], Mat 72 REL3 is well suited to represent close behaviour of concrete to investigate structural behaviour especially under dynamic loads with a higher strain rate. Additionally, only one input parameter (unconfined compressive strength) is required to use this material model and it can be obtained easily from simple experiments [12].Therefore, the present study was conducted implementing this MAT72 REL3 material model for concrete.
Plastic kinematic material model available in LS DYNA was selected to model reinforced steel in current structural models [6, 12]. It represents an elastic plastic material model with strain rate effect.

Material behaviour under a rapidly loading environment is remarkably different from in static loads because a material is unable to deform at a normal rate as in static loadings subjected to rapid load conditions [8, 12]. This creates an enhancement in the stress level of the yielding. As a result, a structural member will increase its strength in excess of their static capability. Figure 6 demonstrates a typical range of strain rates for several loading conditions [8].Therefore, strain rate effect must be taken into consideration in blast load analysis for more reliable outcomes.

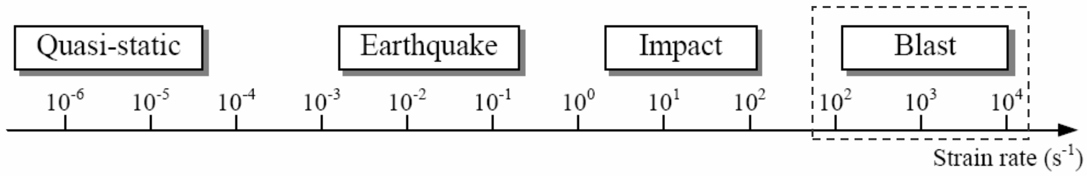


Figure 6; Strain rates for different loading conditions [8]

The typical stress-strain curves of concrete at different strain rates are indicated in Figure 7. It clearly shows that concrete strength increased with high strain rate.

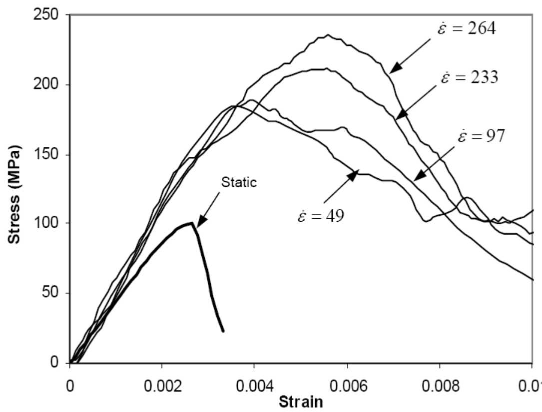
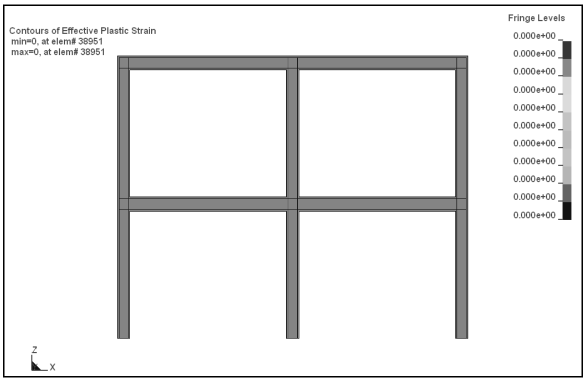


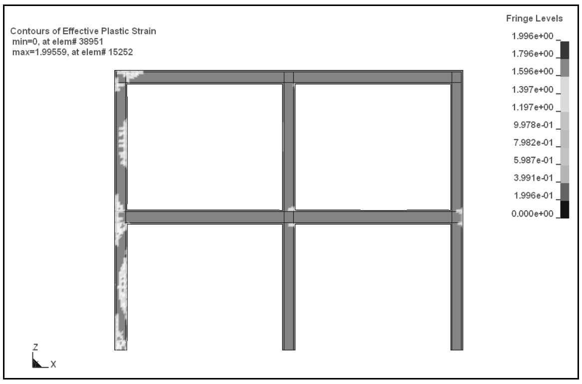
Figure 7: Stress-strain curves of concrete at different strain rates [8].

3.2.3 Structural Analysis and Observations

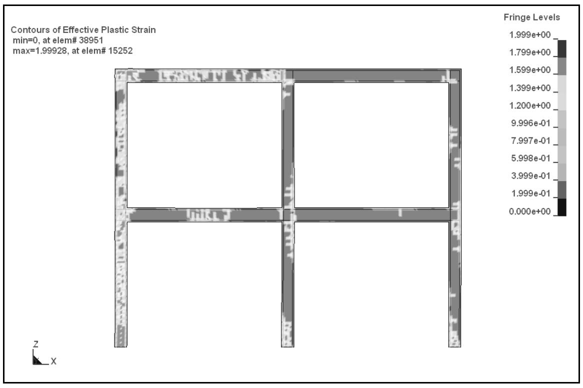
Structural analysis was conducted for six blast loading cases with charge weights of 150, 350, 420, 500, 650 and 700 kg of TNT and unique stand off distance of 10 m. Time history analyses were carried out in LS DYNA. Initially, vertical gravity loads were applied for each RC frame to represent the normal dead and live loads, applied as a ramp function of time. Ramp loading was used to avoid stress concentration at loading regions due to rapid loading. After 70 seconds time history analysis, when the vertical load variation (and hence the structure response) had stabilised, blast load for one of the loading cases was applied as pressure loads on the front face of the left columns. The time history analysis was continued for another 230 ms and the response of the frame was evaluated. Figure 8 illustrates the strain variation of the frame over time and clearly shows the strain/stress propagation in the frame members and the damage locations. Damage in the frame was progressive as indicated in Figure 8. In order to assess the pre and post blast axial capacities of the columns, equal, but slowly varying vertical displacements were imposed at the top of the columns at these stages. The maximum values of the base reactions for these two events were evaluated and these represent the pre and post event axial capacities of the columns. These capacities were then used to calculate the damage indices of the columns for a given blast event.



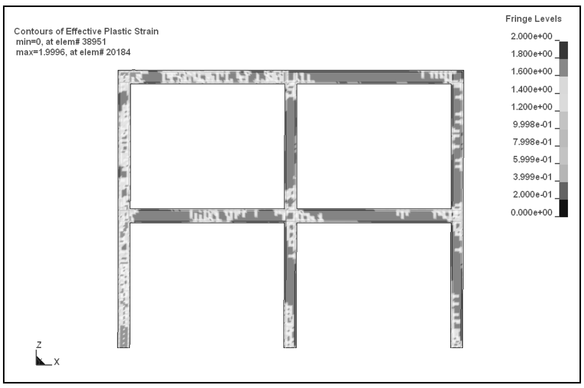
(a) Before blast load



(b) Response at 75ms



(c) Response at 80ms



(d) Response at 200ms

Figure 8; Strain variation of the frame with time after the explosion

The above procedure was repeated for all 6 blast loading cases. These studies indicated the feasibility of investigating the blast response of reinforced concrete frames using LS DYNA with all related parameters and with material properties under high strain rates. It is therefore evident that this type of global analysis is significant and necessary to understand the behaviour of structural components such as columns or beams. Analysis of individual single elements (as carried out in previous research) may produce inappropriate results due to wrong assumptions for boundary conditions [12, 14].

Parametric studies can then be performed accurately to derive desired information. Figure 9 shows residual lateral displacement of first floor for the different blast loading cases. It can be seen that residual displacement varies in a non-linear manner and increasing gradient, with blast pressure for a constant stand off distance.

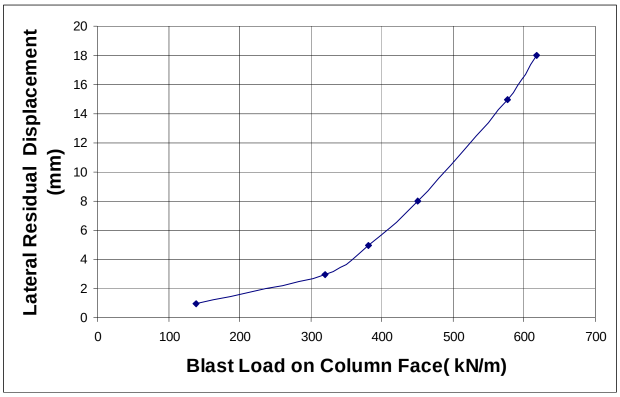


Figure 9; Residual lateral displacement of first floor

The analysis results also indicate that blast effect influences the entire frame, although severe damage created by the explosion is highly localised. Therefore damage investigations have to be focused to evaluation of local element behaviour after the incident. Damage assessment for front column was then evaluated here.

3.2 3 Damage Index.

Damage index numerically indicates the level of damage a particular structure or a component [12, 14]. This is a valuable tool in evaluation and design to resist disasters such as an earthquake or blast [2, 15]. However, limited numerical derivations have been carried out to identify the damage indices under explosion load and most have focused on a single structural component individually to calculate it [12, 14]. Damage indices based on residual capacity of damage structure may offer most reliable estimation on damage because remaining life of the structure would depend upon it. Therefore, a global evaluation is necessary for better prediction of the behaviour of the entire structure or its elements. In this paper, the damage index is defined based on residual load carrying capacity of the remaining can be illustrated as;

$$DI = 1 - \frac{P_{\mathrm{Re}idual}}{P_{Original}}$$

Where $P_{Residual}$ is the residual loading carrying capacity of the damage RC frame (or element) and $P_{original}$ is the normal carrying capacity of RC frame (or element) without damage. A columns vertical load carrying capacities of the LS DYNA model were measured with and without blast loads to calculate a vertical damage index for column with respect to each blast load scenarios in present study. Variation of damage index of ground column with respect to load and impulse are shown in the table 1. It is graphically illustrated in figure 10.

Load (kN)	Impulse (kNms)	DI
139	315	0.04
319	655	0.09
381	760	0.17
450	856	0.31
577	1048	0.67
618	1121	0.81

Table1; Damage index with load and impulse

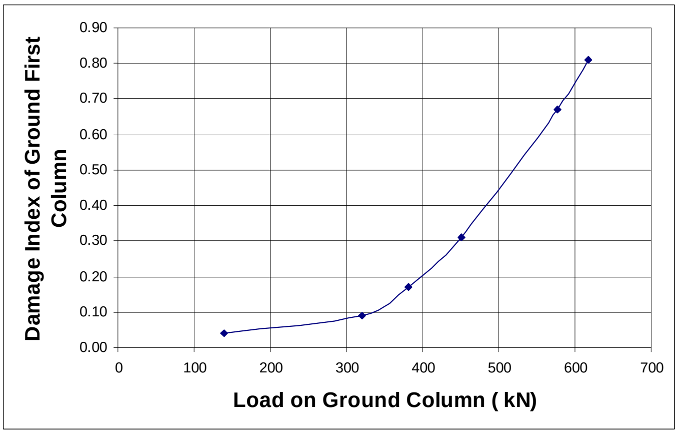


Figure 10; Damage index of first column variation with face load

Research is continuing and the next stage will deal with damage prediction and residual capacity analysis of frames (columns and beams) in 5, 10, 15 and 20 storey buildings under external bomb incidents.

4. Conclusion.

The importance of damage and residual capacity analysis of buildings has been pointed out. A computer model of a simple 2D RC frame was developed for studying the blast response and evaluating the residual capacity of the columns, using the software LS DYNA. The important steps in the procedure such as initial ramp loading to represent normal gravity loads followed by application of blast loads and the application of vertical displacement to the frame to evaluate the column residual capacities have been described. Damage evaluation based on residual capacities through global analysis is proposed for easy identification of the state of damage which is required in post blast assessments. Parametric studies will then be carried out to identify key factors of influence.

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